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Proceedings of the ARPA/AFML Review of Progress in Quantitative NDE, September 1976–June 1977

Interdisciplinary Program for Quantitative Flaw Definition Annual Reports

5-1978

Ultrasonic Imaging Systems

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Kino, Gordon S.; Waugh, T.; and Corl, D., "Ultrasonic Imaging Systems" (1978). *Proceedings of the ARPA/AFML Review of Progress in Quantitative NDE, September 1976–June 1977*. 63.
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Ultrasonic Imaging Systems

Abstract
The use of ultrasonic imaging systems for non-destructive evaluation is increasing, with particular interest being paid to research into real time and quasi-real time imaging systems. Photos are shown which were taken using an electronically scanned and focused real time ultrasonic imaging system. The system can be operated with longitudinal waves, shear waves, Rayleigh waves, and lamb waves in the 1.5 MHz to 3.5 MHz frequency range, and has been successfully used on composite materials (boron fiber epoxy on titanium) and on a number of metals (steel, aluminum, and titanium). This system has been operated in both transmission and reflection modes; examples of each are shown.

Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering

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ULTRASONIC IMAGING SYSTEMS

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ABSTRACT

The use of ultrasonic imaging systems for non-destructive evaluation is increasing, with particular interest being paid to research into real time and quasi-real time imaging systems. Photos are shown which were taken using an electronically scanned and focused real time ultrasonic imaging system. The system can be operated with longitudinal waves, shear waves, Rayleigh waves, and Lamb waves in the 1.5 MHz to 3.5 MHz frequency range, and has been successfully used on composite materials (boron fiber epoxy on titanium) and on a number of metals (steel, aluminum, and titanium). This system has been operated in both transmission and reflection modes; examples of each are shown.

Results Obtained on an Electronically Scanned and Focused Imaging System

During the last three years, a new type of electronically scanned and focused acoustic imaging system has been demonstrated for use in non-destructive testing applications. The system has been operated in A-scan, B-scan, and C-scan testing modes and has demonstrated increases in speed of as much as 100 times that of an equivalent mechanically scanned system while producing images which are easily recognizable by a human operator and which produce information on the two-dimensional location of its size and shape. As far as we are aware, this is the first electronically scanned and focused imaging system that has been used in NDT applications.

Consider the application of the system in a C-scan mode. With a normal mechanical scan, illustrated in Fig. 1, a focused receiver and transmitter would be used to obtain definitions of the order of 1 mm. It might take many hours to scan a raster to produce a visual display of a large object. In an equivalent electronically scanned system, illustrated in Fig. 2, arrays of as many as 100 transducer elements are employed in the transmitter and receiver. By electronic signal processing, the beam can be focused and scanned along a line parallel to the array in less than 60 μsec. The method employed makes use of surface acoustic wave technology, and employs a surface acoustic wave delay line with one tap per element of the array. By this means, a phase reference is introduced which is equivalent to the action of a physical lens. The electronic lens behaves like a physical lens which scans a line in the x direction parallel to the array at a rate comparable to the acoustic velocity in the medium; the focal length of this lens can be changed electronically, at will. At the present time, the definition in the perpendicular direction, the y direction (parallel to the array surface) is controlled either by a slit in front of the object or by a physical lens, or, alternatively, by the width of the beam itself. Scanning in the vertical direction is still arranged mechanically, but now, because of the use of 100 elements in the array, the basic scanning speed has been increased by 100 times.

An acoustic image of a boron fiber reinforced epoxy laminate laid down on titanium, supplied to us by E. Caustin of the Los Angeles Division, Rockwell International, is shown in the upper display of Fig. 3 with an illustration of the voids in the original panel. It will be seen that the device picks out most of the defects very clearly.

The system can also be operated with electronic scanning in both the x and y directions by using crossed arrays. We have done relatively little with this mode of operation. For completeness, a result taken of the letter "S" cut into a piece of rubber is shown in Fig. 4.

Most of our work has been devoted to B-scan imaging. The basic operation of the system is illustrated in Fig. 5. In this mode of operation, the array focusing system can be regarded as a moving lens which is scanned at a velocity comparable to the acoustic velocity in the medium itself. The system is first operated as a transmitter. It is focused on a line a distance z from the array, and, thus, scans this line. At a time 2T later, where $T = z/v_a$ and v_a is the velocity of an acoustic wave in the medium, the device is operated as a moving receiver lens, so that it picks up a signal from a point which has been illuminated at a time 2T before. A signal arriving from a more distant point will arrive after the lens has moved past the received beam, so that there will be good range definition. Similarly, a signal arriving from a different point on the scan line will not be seen, because of the good transverse definition of the lens. Thus, the device has good transverse and range resolution. In practice, the system is used to scan along a line, as shown in Fig. 6, then refocused and the time delay between transmit and receive changed so as to scan a line at a different distance z from the array until a complete raster normal to the array has been scanned.

A simple picture of a step block in water is shown in Fig. 6. It will be noted that both the transverse position and longitudinal position of the steps can be clearly seen; the steps being approximately 8 mm apart and 5 mm wide, the results being taken at an acoustic frequency of 2 MHz.

During the last year the system has been used to take images with various types of waves in metals. As an illustration, we have used 3 MHz longitudinal waves in aluminum to obtain an image of a flat bottomed hole. The results are shown in Fig. 7, where it will be seen that the top surface of the hole can be observed, as well as the front and back walls of the metal sample. The hole has a diameter of 3 mm and a length of 25 mm. It will be noted that the diameter and length of the hole can be measured directly by this technique, without further interpretation of the results. Because the surface of the hole is a specular reflector, we only observe its top surface, a point of great importance in NDT problems. A further point which is important to realize is that, in contradistinction to our earlier imaging system results, we are now able to obtain images of small reflectors very near to large reflectors, like the wall of a sample; the basic difficulty in doing this is that the relatively weak side-lobes of the image from strong reflectors can "swamp out" the weak reflection from a small neighboring flaw. To eliminate this difficulty, we have adopted a method known as "gating the pulse," which makes it possible to look only at the image corresponding to the main lobe of the reflector of interest. This slows the scan rate considerably, but proves feasibility for the rapid scanning system which we are now developing, and is a valid technique for examining small flaws and is still much quicker and more accurate than mechanical scanning.

As a second illustration, in Fig. 8 we show how a shear wave is excited in an aluminum sample, with the shear wave propagating along the axis of the sample, and focused and scanned in a direction perpendicular to the paper. A series of holes cut into the sample are shown in the same figure, and it can be seen that both the transverse and longitudinal position of these holes can clearly be observed.

A similar technique can be used to excite Rayleigh waves and Lamb waves in target plates, as shown in Fig. 9. Some results obtained for Lamb waves are shown in Fig. 10.

Another set of results for Rayleigh waves is shown in Fig. 11. In the first photo, the top and bottom edge of the plate can be seen, for the Rayleigh wave passes over the top surface of the plate and around the edge to the bottom surface. By changing the image intensity, three small 0.5 mm D holes 9 mm from the edge can also be seen.

Finally, we show Rayleigh wave images of an artificial crack 1 cm long, ~100 μm side, eloxed in a metal sample. This sample can be rotated in the surface wave field, so that the crack can be aligned at an angle to the transducer array. When the crack is parallel to the array ($\theta = 0$), the crack is clearly seen, as shown in Fig. 12(a). Because the crack is a specular reflector, when it is turned at an angle no signal will be returned to the array from the middle of the crack; only the two ends of the crack will be observed. The results for $\theta = 0^\circ$, 45°, and 90° are shown in Figs. 12(a), 12(b), and 12(c), respectively. The scattering from the crack ends can clearly be seen. A similar set of results is shown in Fig. 13 for two holes whose diameters are the same as the width of the crack. The results will be seen to be almost indistinguishable from those of a crack, except for the $\theta = 0$ case. But more precise analysis does show differences in amplitudes between the two cases, so that one might expect that a more detailed study would show up considerable differences between a crack and two holes.

These studies confirm the results obtained in theoretical work on this program of scattering from cracks. The two ends of the cracks behave like sources, and the imaging technique shows the presence of the sources directly, rather than resting on an indirect inference based on the interference phenomenon between the two sources, as would be obtained with simple plane wave transducers.

The Design of a New Imaging System

After working with the present imaging system in NDT applications during the last three years, we have obtained considerable insight into its advantages and disadvantages. The advantages are the basic ones to be expected; good definition in two directions, high speed, and large field of view in the direction normal to the array. The disadvantages are, a relatively limited field of view in the direction parallel to the array because of the limited number of array elements used in our research system, complexity, higher sidelobe levels than we would like, at least in the high speed operating mode, a relatively small aperture, so that the range of viewing angles is relatively small thus tending to give ppor images of specular reflectors, and operation at a lower frequency than optimum (2.5 MHz).

In order to eliminate most of these difficulties, we have been examining and experimenting with component parts of a new imaging system. The new system is eventually intended to employ a very long array of elements, perhaps several hundred, or, alternatively, a small hand held array with perhaps 20-30 elements which can be moved by hand over the surface of an object. In each case, only 20-30 elements will be used at a time, thus making the electronic problems of the control circuitry, amplifiers, and other components of the system much simpler. In the purely electronic system, the equivalent of mechanical scanning will be carried out by a multiplexing arrangement to switch the electronic circuits along the way.

The system will be arranged so that from any 30 elements a focused beam will be obtained, which scans over a circular sector of the order of $\pm 40^\circ$ or more, and yields a complete dynamically focused image of this sectorial region of radius up to 20 cm. The process will then be repeated for each position along the long array, or each mechanical position. Equivalent points in the multiple images will be computed and placed at the same point on the cathode ray screen. This is like the operation of the present medical B-scan imaging system, systems which are unfocused and purely mechanically scanned. In that case, the radial sector scanning is obtained by tilting the transducer and relying on the flexibility of the body surface. The operating system will emit a pulse, or train of pulses, from a single highly efficient transducer element, receive the reflected echoes back at the same transducer, and then use an A to D converter to digitize the received signals. The device will then store the digital signals from one transducer element in a RAM and then repeat the process for 29 more elements. With the information stored in the RAMS, we can obtain a complete image of one sector, either by using special purpose CCD's being developed in our own integrated circuit laboratory, or by programming the output taps of the RAMS to compute the image, an operation which can be carried out in real time, if the programs are stored in ROMS. We will then convert the output to analog form, and, thus, produce an intensity display of the image. After moving along the array one step, or changing its mechanical position and keeping track of the position with a support arm of the type used in medical systems, we will then repeat the process, and superimpose the images obtained, using either a scan converter of the type presently available, or its digital form, a type presently coming on the market.

We have tested some of these concepts; an efficient transducer array, the RAM circuitry, simple transmitter and receiver circuits, and inverse filtering circuits, so that we can use long pulse trains to obtain a higher energy in the transmitted signal. All the concepts appear to be feasible. So, we have begun to build a new electronically scanned and focused system which we believe will have a low sidelobe level, be close to real time operation, and operate initially with a maximum frequency of 5 MHz, and eventually at 10 MHz.

Conclusions

We have shown that imaging techniques are very powerful ones for determining the position of the flaw, and for finding information on its size and shape. Careful attention to the design of these imaging systems is necessary to keep the side lobe levels low enough, so that small flaws can be observed in the neighborhood of a large scatterer, such as a metal wall. Feasibility demonstrations of this mode of operation have been made. The operation of these devices is quick and simple, and provides an increase in speed on the order of 100 times over that of a purely mechanically scanned system. In B-scan operation, the transverse definition in these systems is comparable to the range definition, a major advance in capability over present systems.

A new system is being designed which shows promise of being capable of eliminating most of the difficulties associated with our first research system. The concept involved makes use of digital circuitry and memories, which are dropping in price all the time, so it should eventually lead to an inexpensive enough and flexible enough system to make it eventually possible to construct an electronically focused system with full three-dimensional focusing and dynamic scanning.

Acknowledgement

This research was sponsored by the Center for Advanced NDE operated by the Science Center, Rockwell International, for the Advanced Research Projects Agency and the Air Force Materials Laboratory under contract F33615-74-C-5180.

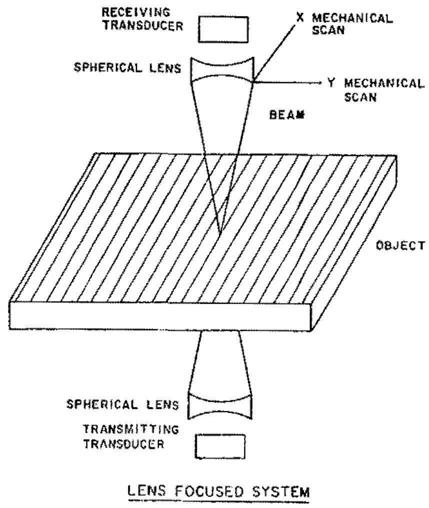


Figure 1. Illustration of typical mechanically scanned transmission system used for nondestructive testing.

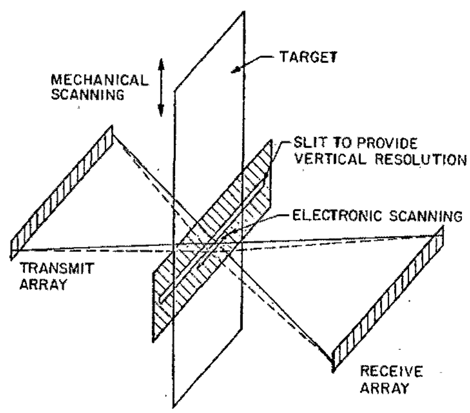


Figure 2. Illustration of system used for electronically scanned transmission imaging.

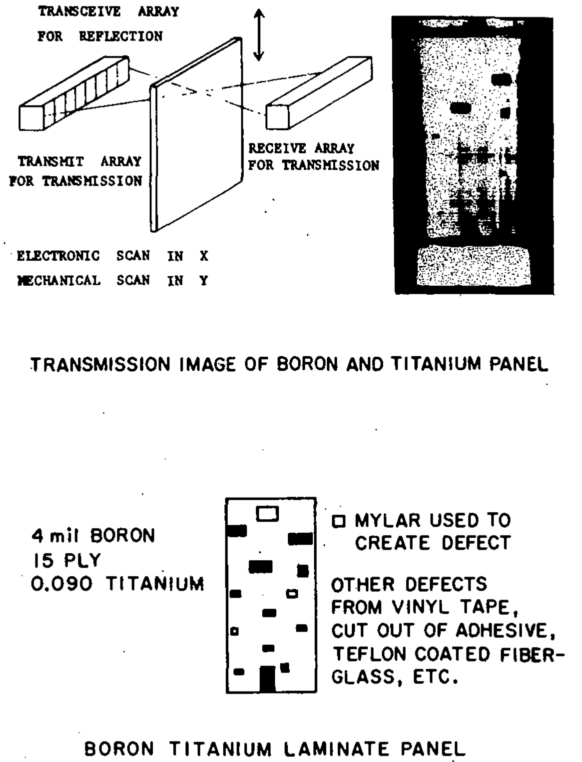


Figure 3. Transmission image of bonded boron fiber reinforced epoxy laminate laid down on titanium, illustrating debonded regions.

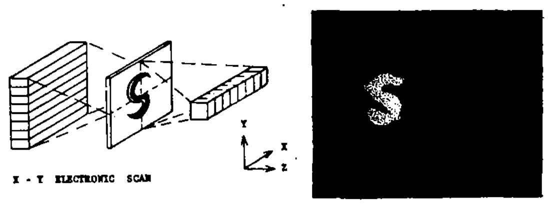


Figure 4. A completely electronically scanned and focused C-scan system, used to image a letter S cut in a piece of rubber.

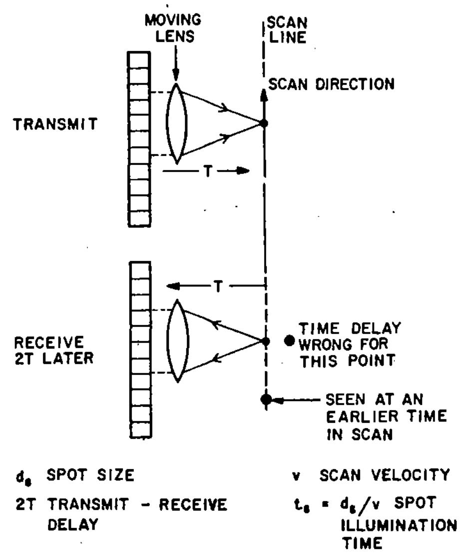


Figure 5. Illustration of the operation of the B-scan system, where it is regarded as a moving lens.

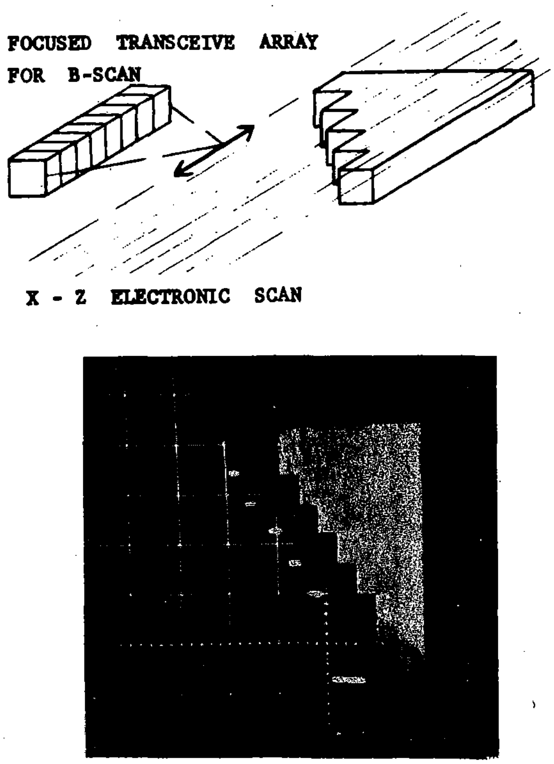


Figure 6. A B-scan image of a stepped sample compared with its optical image. The small steps are 5 mm wide with 8 mm distance between them.

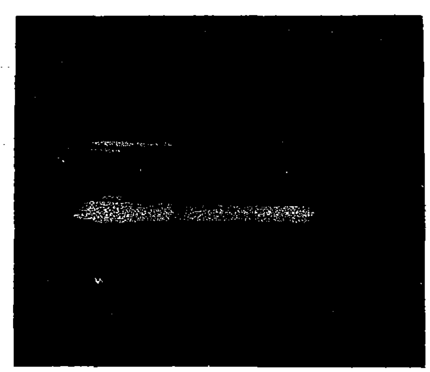
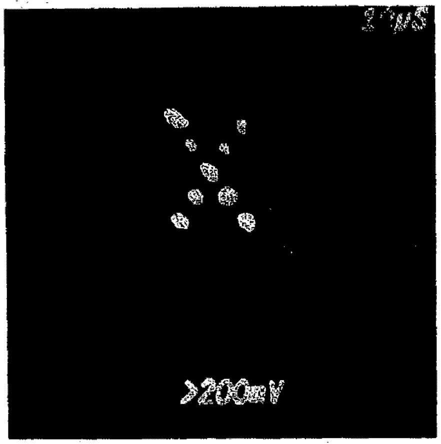
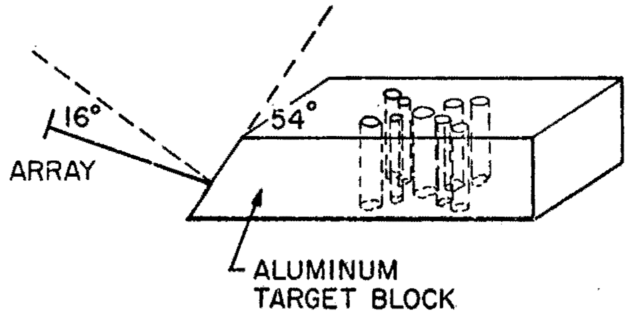


Figure 7. An acoustic image of a flat bottomed hole (3 mm dia. x 25 mm deep) using 3 MHz longitudinal waves in an aluminum sample.



(a)



(b)

Figure 8. 2.75 MHz shear wave B-scan imaging in aluminum. (a) Picture of 2 mm diameter holes in aluminum block. Hole is roughly 25 mm x 50 mm. Center hole is 150 mm fron end of block. (b) Schematic of setup to excite shear waves in aluminum block.

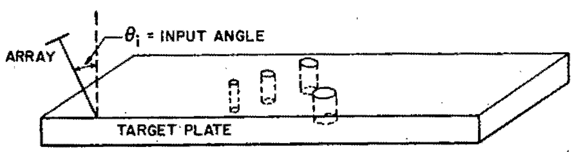
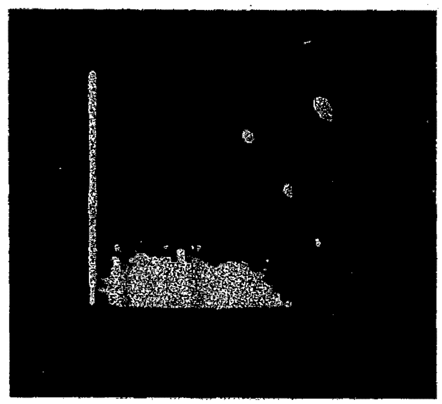
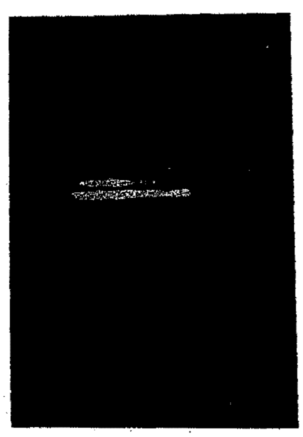


Figure 9. Schematic of setup to excite Rayleigh waves and Lamb waves in target plates. For Rayleigh waves in aluminum θ = 28°.



Fiqure 10. B-scan Lamb wave image. Holes range in size from 1.5 mm diameter to 10 mm diameter. Spacing between holes is on the order of 30 mm.



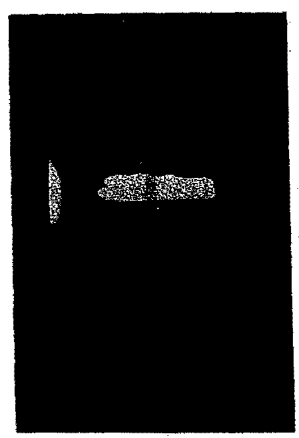


Figure 11. Rayleigh wave imaging in an aluminum target plate. The holes are 1 mm in diameter and 9 mm from the edge of the plate, spaced on 12.5 mm centers on a 1/4 inch thick plate.